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EQUIPMENT

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BASIS FOR THE DEVELOPMENT OF A THREE-CYCLE REGENERATOR FOR A GLASSMAKING FURNACE

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A novel three-cycle scheme is proposed for recovering heat from the flue gases in glassmaking furnaces. The theoretical principles validating the correctness of prescribing the main initial data for calculating a three-cycle regenerator are formulated. An example of the development of a three-cycle regenerator for a glassmaking furnace with a horseshoe flame configuration is presented.

Key words: glassmaking furnace, regeneration schemes, regenerator parameters, enthalpy, temperature, checkerwork.

The composition of glassmaking furnaces is largely determined by the height of the production vessel. The arrangement of a furnace with the glass-forming equipment placed at the zeroth level of a one-floor building presents the greatest difficulty. In this case difficulties arise with the implementation of one- or two-cycle schemes for recovering the heat in the flue gases. Even if the foundation slab beneath the regenerator is placed at depth, for example, at the level –6 m, the nominal height of the checkerwork cannot be guaranteed.

The solution of the problem is to use a three-cycle recovery scheme. Even though a three-cycle regenerator has obvious structural advantages it is not widely used in industry. The practical application of well-known methods of calculating a regenerator is limited to one- and two-cycle recovery schemes [1, 2]. Developed for the conditions of metallurgical furnaces such regenerators do not take account of the specifics of glassmaking furnaces and do not contain the methodological guidelines for the development of three-cycle schemes.

It is well known that the calculation of a regenerator is based on the heat-transfer equation, from which the area of the heating surface of the checkerwork, giving the prescribed heating temperature of the air, is determined:

$$F_{\mathrm{cw}} = \frac{Q_{\mathrm{a}}}{K_{\Sigma}\overline{\Delta t}}, \qquad (1)$$

where F_{cw} is the area of the heating surface of the checkerwork, m^2; Q_{a} is the amount of heat transferred from the flue gases to the air in one cycle of operation of the regenerator, kJ; K_{Σ} is the total coefficient of heat transfer from the flue gases to the air in one cycle of operation of the regenerator, kJ/(m^2 · K); and, $\overline{\Delta t}$ is the logarithmic mean difference of the temperatures, °C.

The parameters in the relation (1) can be calculated if the temperature of the flue gases and air at the entrance and exit from the checkerwork are known. For a one-cycle regenerator, as a rule, the following are given: the temperature at the entrance and exit from the checkerwork (t''_{a} and t'_{a}, respectively, °C) and the temperature of the flue gases at the entrance into the checkerwork (t'_{fg}, °C). The temperature of the flue gases at the exit from the checkerwork (t''_{fg}, °C) is found from the enthalpy of the flue gases determined from the equation of heat balance

$$V'_{\mathrm{fg}}(i'_{\mathrm{fg}} - i''_{\mathrm{fg}}) = V_{\mathrm{a}}(i'_{\mathrm{a}} - i''_{\mathrm{a}}) + m_{\mathrm{a}}V'_{\mathrm{fg}}\,[0.5(i'_{\mathrm{fg}} + i''_{\mathrm{fg}}) - i_{\mathrm{a}}], \qquad (2)$$

where V'_{fg} is the flow rate of the flue gases at the entrance into the checkerwork, nm^3/sec; V_{a} is the flow rate of the heated air, nm^3/sec; i'_{fg}, i'_{a} and i''_{fg}, i''_{a} are the enthalpy of the flue gases and air at the entrance and exit from the checkerwork, respectively, kJ/m^3; i_{a} is the enthalpy of the air drawn into the regenerator, kJ/m^3; m_{a} is the coefficient of air intake; and, the coefficient ç takes account of the heat losses through the regenerator brickwork.

The calculation of a three-cycle regenerator is based on the Eqs. (1) and (2) and presupposes successive determina-

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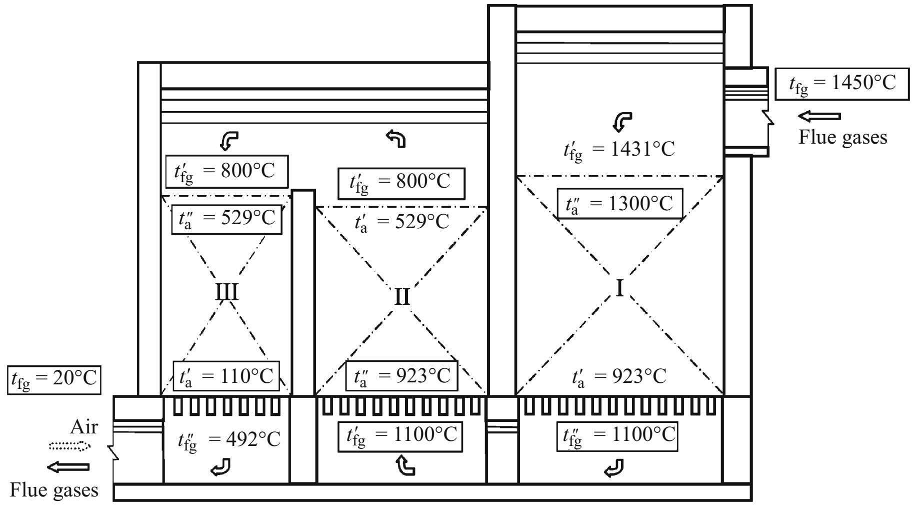

Fig. 1. Computational scheme of a three-cycle regenerator of a glassmaking furnace with horseshoe flame: I – III) hot, middle and cold chambers, respectively; in frame) prescribed values of the temperature.

tion of the area of the heating surface of the checkerwork in each chamber. Three temperatures of the gas media in each chamber must be prescribed, and one temperature (of the flue gases or air) is found from the enthalpy determined from Eq. (2). In all chambers of the regenerator the parameters of the flue gases and air at the entrance and exit from the checkerwork are designated at (′) and (″), respectively.

The exposition given below of the theoretical positions of this paper is illustrated for the calculation of a three-cycle regenerator of a furnace with a horseshoe flame (see Fig. 1). We take V'_{fg} = 5.064 and V_a = 4.328 nm^3/sec. The total losses of the heat through the brickwork of the regenerator are 3% of the heat content of the flue gases at the exit from the furnace [3]. The heat losses through the flue gases before the entrance into the checkerwork of the hot chamber are 1.5%. According to the height of the checkerwork of the hot, middle and cold chambers are given by the coefficients η = 0.993, 0.995 and 0.997, respectively. The air intake through the brickwork is taken to be 10% of the flow rate of the flue gases at the entrance into the regenerator [3]. The magnitudes of the air intake into the hot, middle and cold chambers are 5, 3 ad 2% of 0.1 V'_{fg}, respectively. The following temperatures are also given: flue gases at the exit from the furnace t_{fg} = 1450°C, air drawn in t_a = 20°C, air at the entrance into the checkerwork of the cold chamber (t'_a = 110°C) and air at the exit from the checkerwork of the hot chamber (t''_a = 1300°C). The temperature of the flue gases at the entrance into the checkerwork of the hot chamber (t'_{fg} = 1431°C) is determined by making the product of the specific heat capacity of the flue gases by their temperature approach the computed value of the enthalpy: $i'_{fg} = c'_{fg} t'_{fg} = 0.985 i_{fg}$ = 2329.6 kJ/m^3 ($i_{fg} = c_{fg} t_{fg}$ is the enthalpy of the flue gases at the exit from the furnace, c_{fg} is the specific heat of the flue gases at t_{fg}). It is obvious that additional initial data on the heat temperatures of the gas media in each chamber of the regenerator are required in order to continue the calculation.

On the basis of the operating conditions of refractories the checkerwork is divided along the height of the regenerator into three zones: high-temperature, condensation of sulfates and low-temperature. The division of the checkerwork into zones is due to the particularities of the chemical composition and the behavior of the corroding substances in the regenerator of the glassmaking furnace during cooling. The computed boundary separating the zones passes along the temperature of the flue gases 1100 and 800°C, bounding the zone of condensation of sulfates [4]. Different refractory materials are used together with the fixed values of the temperature of the flue gases for the brickwork of the checkerwork and walls in the indicated zones [3]. For this reason the distribution of the zones of the checkerwork over the separate chambers of the regenerator is fully substantiated, including from the operational standpoint (see Fig. 1).

It should be noted that the use of the characteristic temperatures 1100 and 800°C of the flue gases as initial data integrates the object of the calculation (checkerwork) into a whole, comprised of three spatially separated parts. For example, the value 1100°C characterizes the temperature of the flue gases at the exit from the checkerwork of the hot chamber and at the entrance into the checkerwork in the middle chamber. In turn the temperature 800°C of the flue gases determines the degree to which they are heated at the exit from the checkerwork of the middle chamber and at the entrance into the checkerwork of the cold chamber.

In summary, in the case of the hot chamber only the temperature of the air at the entrance into the checkerwork remains unknown. Expressing from Eq. (2) the enthalpy of air at the entrance into the checkerwork and substituting the values of the parameters characterizing the checkerwork in the hot chamber we obtain i'_a = 1292.7 kJ/m^3. This value of the enthalpy of air corresponds to t'_a = 923°C.

Performing similar operations for the checkerwork of the middle chamber with t''_a = 923°C (see Fig. 1) we obtain i'_a = 713.8 kJ/m^3 and, correspondingly, t'_a = 529°C.

In the cold chamber (see Fig. 1), since $t''_{a} = 529°C$, the temperature of the flue gases at the exit from the checkerwork remains unknown. We find from Eq. (2) the enthalpy of the flue gases at the exit from the checkerwork. The quantity $i''_{fg} = 738.9$ kJ/m^3 corresponds to the temperature of the flue gases at the exit from the checkerwork of the cold chamber $t''_{fg} = 492°C$.

In the following calculations the average values of the parameters of the checkerwork in each chamber of the regenerator are used, including the average temperatures of the flue gases and air: $\overline{t_{fg}} = 0.5(t'_{fg} + t''_{fg})$ and $\bar{t} = 0.5(t' + t'')$.

In designing a regenerator it is of fundamental importance to prescribe the velocity of the flue gases in the checkerwork: its value has opposite effects on the effectiveness of the convection heat transfer and stability of the checkerwork material. On the one hand the higher the velocity of the flue gases, the larger the coefficient of convection heat emission and the smaller the computed area of the heating surface of the checkerwork are. On the other hand the lower the velocity of the dust-contaminated gas flow, the higher the operating stability of the checkerwork is. A checkerwork system with direct *Topfstein* wells (RHI Company) is used in modern glassmaking furnaces. For definite values of the velocity of the flue gases the use of blocks of the type TL or TG makes it possible to obtain a laminar gas flow in the checkerwork. In this case the products of condensation of the component of the flue gases and corrosion of the refractory material do not penetrate into the side wall of the blocks. They concentrate in the middle part of the channels and settle on the bottom of the sub-checkerwork chamber of the regenerator. For this reason, since the checkerwork is required to function maintenance-free for 8 – 9 yr, the velocity of the flue gases must correspond to the laminar gas flow in all chambers of the regenerator.

The average velocity of the flue gases and air in the checkerwork under actual conditions is found from the expressions

$$\overline{w_{fg}} = \overline{w_{0fg}}\left(1 + \frac{\overline{t_{fg}}}{273}\right); \tag{3}$$

$$\overline{w_{a}} = \overline{w_{0fg}}\,\frac{V_{a}}{\overline{V_{fg}}}\,\frac{p_{0a}}{p_{a}}\left(1 + \frac{\overline{t_{a}}}{273}\right), \tag{4}$$

where $\overline{w_{fg}}$ and $\overline{w_{a}}$ are the average velocities of the flue gases and air, respectively, m/sec; $\overline{w_{0fg}}$ is the average velocity of the flue gases under normal conditions, m/sec; $\overline{V_{fg}}$ is the average, taking account of the air drawn in, flow rate of the flue gases through the checkerwork, m^3/sec; and, p_{0a} and p_{a} are, respectively, the absolute value of the air pressure under normal and actual conditions, in Pa.

It follows from Eqs. (3) and (4) that the velocity of the flue gases and air under real conditions is determined by the parameter $\overline{w_{0fg}}$, whose value must be prescribed for each chamber of the regenerator. This condition is necessary, since together with the hydraulic regime the velocity of the flue gases under normal conditions determines the geometric dimensions of the checkerwork.

The volume of the checkerwork is calculated from the relation

$$V_{cw} = \frac{F_{cw}}{f_1}, \tag{5}$$

where V_{cw} is the volume of the checkerwork, m^3; f_1 is the specific area of the heating surface of the checkerwork, m^2/m^3.

We find from the relation $V_{cw} = H\Omega$

$$H = \frac{F_{cw}}{\Omega}, \tag{6}$$

where H is the height of the checkerworks, m, and Ω is the area of the cross section of the checkerwork, m^2.

In turn

$$\Omega = \frac{\omega}{f_2}, \tag{7}$$

where $\omega = \overline{V_{fg}}/\overline{w_{0fg}}$ is the area of the live cross section of the checkerwork, m^2; f_2 is the specific area of the live section of the checkerwork, m^2/m^3.

The second golden section can be used to pick the approximate length and width of the transverse section of the checkerwork:

$$\frac{A}{B} = \frac{56}{44},$$

whence

$$A = \sqrt{\frac{56\Omega}{44}} \quad \text{and} \quad B = \sqrt{\frac{44\Omega}{56}},$$

where A and B are, respectively, the length and width of the transverse section of the checkerwork, m.

The width of the checkerwork must satisfy the experimentally determined relation

$$B \geq (1.7 - 1.8)b_{c}, \tag{8}$$

where b_{c} is the width of the refractory channel coupling the working space of the furnace and the regenerator, m.

The parameters f_1 and f_2 are the geometric characteristics of the checkerwork. For example, for the block TL 14/175 they equal 16.6 and 0.578 m^2/m^3, respectively. It should also be noted that in order to secure a uniform distribution of the gas flow over the cross section of the checkerwork the following relation must be satisfied:

$$k_{order} = \frac{H}{\sqrt{\Omega}} \geq 1.1, \tag{9}$$

where k_{order} is the orderliness factor of the checkerwork.

TABLE 1. Computational Parameters of a Three-Cycle Generator of a Glassmaking Furnace with a Horseshoe Flame and Prescribed Velocity of the Flue Gases (Under Normal Conditions) in the Hot Chamber

Parameter	Hot chamber			Middle chamber			Cold chamber		
$\overline{w_{0fg}}$, m/sec	0.30	0.35	0.40	0.38	0.44	0.50	0.50	0.58	0.67
F_{cw}, m^2	2473.5	2290.5	2135.0	1778.4	1639.3	1528.9	1414.8	1317.2	1227.3
V_{cw}, m^3	149.0	138.0	128.4	107.1	98.8	92.1	85.2	79.3	73.9
Ω, m^2	29.9	25.6	22.5	24.6	21.3	18.7	19.0	16.4	14.2
A/B, m	6.2/4.8	5.7 /4.5	5.4/4.2	5.1/4.8	4.7/4.5	4.4/4.2	3.9/4.8	3.6/4.5	3.4/4.2
H, m	5.0	5.4	5.7	4.4	4.6	4.9	4.5	4.8	5.2
$\overline{w_{fg}}$, m/sec	1.69	1.97	2.25	1.69	1.97	2.25	1.69	1.97	2.25
$\overline{w_a}$, m/sec	1.25	1.44	1.64	1.08	1.26	1.44	0.83	0.96	1.11
$\overline{\mathrm{Re}_{fg}}$*	1050.9	1225.0	1399.1	1511.7	1778.4	2012.6	2360.0	2751.0	3142.0
k_{order}	0.91	1.07	1.20	0.87	1.00	1.13	1.03	1.18	1.38

* $\overline{\mathrm{Re}_{fg}}$ is the average value of the Reynolds number for the flue gases. See text for all other notation.

If the condition for laminar flow of gas in the checkerwork imposes a restriction on the maximum value of the velocity of the flue gases under normal conditions, then the relation (9) limits its minimum value. Therefore, in the case of a three-cycle regenerator, some rational quantity $\overline{w_{0fg}}$ chosen experimentally from the range of values of this parameter must be prescribed for each chamber. The complexity and difficulty of such a solution is obvious. In the opinion of the present author, the velocity of the flue gases under normal conditions is best prescribed only for the checkerwork of the hot chamber. The actual velocity of the flue gases in this chamber as determined from Eq. (3) is assumed to be prescribed for the middle and cold chambers of the regenerator. Then the desired quantity $\overline{w_{0fg}}$ for these chambers is determined from Eq. (3) with the corresponding average value of the temperature of the flue gases $\overline{t_{fg}}$.

In summary, in order to calculate the actual values of the velocity of the flue gases and air in the three chambers of the regenerator it is necessary to prescribe $\overline{w_{0fg}}$ only in the hot chamber. The method proposed for calculating the velocity regime of the regenerator on the basis of the condition $\overline{w_{fg}}$ = const, not only simplifies the computational procedure but it also takes account of the physical coupling of its constituent parts, prescribed by the constant value of the actual velocity of the flue gases.

We now turn to the computational results obtained for the three-cycle regenerators (Table 1). They attest to the fact that all the conditions limiting the design solutions for the regenerator hold only for $\overline{w_{0fg}} = 0.4$ m^2/sec together with the laminar flow regime of the gas flow. A graphical depiction of a three-cycle regenerator with geometric dimensions corresponding to $\overline{w_{0fg}} = 0.4$ m^3/sec is presented in Fig. 1.

In closing we note that the theoretical principles formulated in this work for calculating a three-cycle scheme for recovering the heat contained in the flue gases can be used as a basis for developing modern three-cycle regenerators for glassmaking furnaces.

REFERENCES

1. V. G. Lisienko and V. B. Kut'in, *Heat Engineering: Heat-Exchange Apparatus of Metallurgical Furnaces* [in Russian], UPI im. S. M. Kirova, Sverdlovsk (1982).
2. Ya. M. Gordon, B. F. Zobnin, M. D. Kazyaev, et al., *Heat-Engineering Calculations of Metallurgical Furnaces* [in Russian], Metallurgiya, Moscow (1993).
3. V. Ya. Dzyuzer, "Energy-efficient structure of the masonry of high-temperature regenerator of a glassmaking furnace," *Novye Ogneupory*, No. 2, 3 – 6 (2014).
4. V. Ya. Dzyuzer, "Boundary conditions for calculating the regenerator and checker brickwork in a glassmaking furnace," *Steklo Keram.*, No. 7, 7 – 10 (2013); V. Ya. Dzyuzer, "Boundary conditions for calculating the regenerator and checker brickwork in a glassmaking furnace," *Glass Ceram.*, **70**(7 – 8), 241 – 244 (2013).